SiEUGreen
Sino-European innovative green and smart cities

Sino-European Innovative Green and Smart Cities

D 2.3

Blue Technology (T2) Ready- 1

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The project has received funding from the European Union's Horizon 2020 Research, and Innovation programme, under grant Agreement N 774233 and from the Chinese Ministry of Science and Technology.

Throughout SiEUGreen's implementation, EU and China will share technologies and experiences, thus contributing to the future developments of urban agriculture and urban resilience in both continents.

The project SiEUGreen aspires to enhance the EU-China cooperation in promoting urban agriculture for food security, resource efficiency and smart, resilient cities.

The project contributes to the preparation, deployment and evaluation of showcases in 5 selected European and Chinese urban and peri-urban areas: a previous hospital site in Norway, community gardens in Denmark, previously unused municipal areas with dense refugee population in Turkey, big urban community farms in Beijing and new green urban development in Changsha Central China.

A sustainable business model allowing SiEUGreen to live beyond the project period is planned by joining forces of private investors, governmental policy makers, communities of citizens, academia and technology providers.

Technical References

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[1] **PU** = Public
PP = Restricted to other programme participants (including the Commission Services)
RE = Restricted to a group specified by the consortium (including the Commission Services)
CO = Confidential, only for members of the consortium (including the Commission Services)

Document History			
Version	**Date**	**Author – Partner**	**Summary of Changes**
0.7	06/06/2019	NMBU	Initial Draft
0.8	20/06/2019	NMBU, NIBIO	Revised version based on comments from NMBU and NIBIO
0.9	28/06/2019	NMBU, NIBIO	Final draft version submitted to project coordinator (NMBU) for final review
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3.0	23/10/2019	NMBU, NIBIO	Comments received from Commission on 14/10/2019 incorporated.
4.0	19/12/2019	NMBU	Comments received from Commission on 05/12/2019 incorporated.

Executive Summary

The SiEUGreen project aims to enhance the EU-China cooperation in promoting urban agriculture for food security, resource efficiency, and smart, resilient cities. Circular economy and utilization of domestic organic urban waste resources for the production of fertilizer and soil amendment products for urban and peri-urban agriculture, as well as energy for local use, are essential aspects of the showcases in Fredrikstad and Changsha, especially. The conversion of waste resources and water handling in the SiEUGreen project termed Blue Technology. This deliverable, D2.3 "Blue Technology (T2) Ready 1", is based on research and investigations carried out in the first 18-month project period. We have evaluated four blue technologies related to the processing of liquid waste for recycling in the SiEUGreen showcases: (1) Liquid Bio-digestate anaerobic digestion as a source of plant nutrients, (2) Struvite precipitation from anaerobic digestion and urine, (3) Production of microalgae from biogas digestate and (4) Nitrification of liquid waste. The latest updated status and the potential challenges in the implementation of these technologies in SiEUGreen showcases are provided in fact sheets. Presentation in fact-sheets facilitates later upgrading to practice abstracts.

Human excreta (blackwater) and organic household waste (OHW) contain high amounts of plant nutrients and organic matter, but may also contain pathogens and residues of pharmaceuticals or personal care products (PPCP´s). To utilize the energy in the waste, biogas is produced. Biogas production is covered in D2.1. The potential of anaerobic liquid digestate as a source of plant nutrient recovery was tested. Liquid bio-digestate contains essential and readily available plant nutrients. However, the direct application of liquid digestate as fertilizer has been challenged because of health-related risks. Recent studies on post-treatment of the anaerobically digested effluent of source-separated blackwater demonstrated is an essential step for safe and sustainable recycling and reuse of these renewable resources.

Precipitation of struvite from urine and anaerobically treated blackwater has been investigated in the NMBU laboratories. For developing an efficient way of producing struvite from urine and anaerobically treated liquid digestate, Seawater and $MgCl_2$ have been tested as magnesium sources. Moreover, the electro flocculation technique has been tested as an alternative method. Preliminary results of experiments on urine and anaerobically treated blackwater for struvite precipitation using seawater and Mg-plates (with and without current) demonstrated promising options as alternative sources for Mg. However, the fertilizer quality and effect of struvite precipitated from anaerobically digested blackwater and organic household waste on plant production will be further investigated in the showcases.

Microalgae are fast-growing photosynthetic organisms, which have the potential to be exploited as an alternative source of feed and food additives, biofertilizers, etc. In a separate project, the production of microalgae biomass using liquid biogas digestate as alternative means of nutrient recovery has been tested and promising results have been obtained.

It is proposed to demonstrate both struvite and algae production from filtered digestate in the Fredrikstad showcase. Algae can be used for fodder or as an organic fertilizer.

Nitrification of liquid waste is another important liquid fertilizer processing technique. Nitrification of urine is tried in the NIBIO laboratories. Two types of reactors were tested in a laboratory-scale using stored human urine with a 5-50% dilution rate: 1) a moving bed bioreactor (MBBR) and 2) a multipass paced-bed biofilter using porous lightweight aggregates. A smell-free and chemically stable liquid fertilizer product was obtained. Both the MBBR and biofilter appear to be suitable methods for urine nitrification making an attractive fertilizer for urban gardens.

Further studies will be performed during showcase implementation for removal of PPCP´s and the fertilizer quality of different products.

Table of Contents

1. Introduction

The innovative technologies to be implemented at showcases within SiEUGreen are categorized as Green technologies; Blue technologies and yellow technology. The green technology concerns with soil-based traditional plant growing, water-based hydroponic culture (soilless) and aquaponics (fish and plant), paper-based plant growing technology, greenhouse technology.

The blue technologies classify into water and waste management, production of fertilizer and soil amendment from waste, resource recycling. The yellow technology includes biogas production from waste resources, seasonal solar storage, combined heat and power, and photovoltaic generation of electricity.

These technologies will be implemented in the five SiEUGreen showcases in Europe and China. These technologies will reduce water consumption, facilitate recycling of nutrients to urban and peri-urban agriculture and thus, almost eliminate pollution of surface water. Biogas production from toilet waste (blackwater) and organic household waste (OHW) is a key treatment technology. CO2, heat and power from biogas combustion is utilized together with the nutrient rich solution in a super-insulated greenhouse for local resource reuse and year around plant production.

This deliverable provides documentation for the full-scale implementation part of the blue technologies as well as the yellow technologies needed to showcase SiEUGreen´s vision of circular economy practiced in an urban setting. The remaining blue technologies are presented in D2.4.

Chapter 2 of this deliverable provides brief overview of the SiEUGreen technologies for wastewater management. The chapter also describes the readiness level of the technologies selected for implementation.

Chapter 3 presents the fact sheets on the blue technologies associate with the processing of waste for recycling.

Chapter 4 presents the data that are collected after the implementation of the technology in the showcases

Annex 1 Presents the laboratory scale research experiments carried out in the research facilities of NMBU and NIBIO for preparing the liquid byproduct of the biogas reactor to utilize in the balcony gardens and the green houses for soil amendments.

Annex2 Presents the details of the technology ready for implementation in the Fredrikstad showcase

2. Showcase technologies for water and wastewater reuse

2.1 Overview of technologies for showcase deployment

The technologies under SIEUGreen that will focus on the reuse of various resources including land, water, waste nutrient, solar energy and biogas have already been established in the SiEUGreen grant agreement. The concept demonstrates a strong focus on agricultural food production with zero or minimum transport, solar energy utilization, water saving and wastewater reuse, waste recycling, residents involvement and organic green UA for smart city residents. The SiEUGreen model of recyclable resources is presented in figure 1.

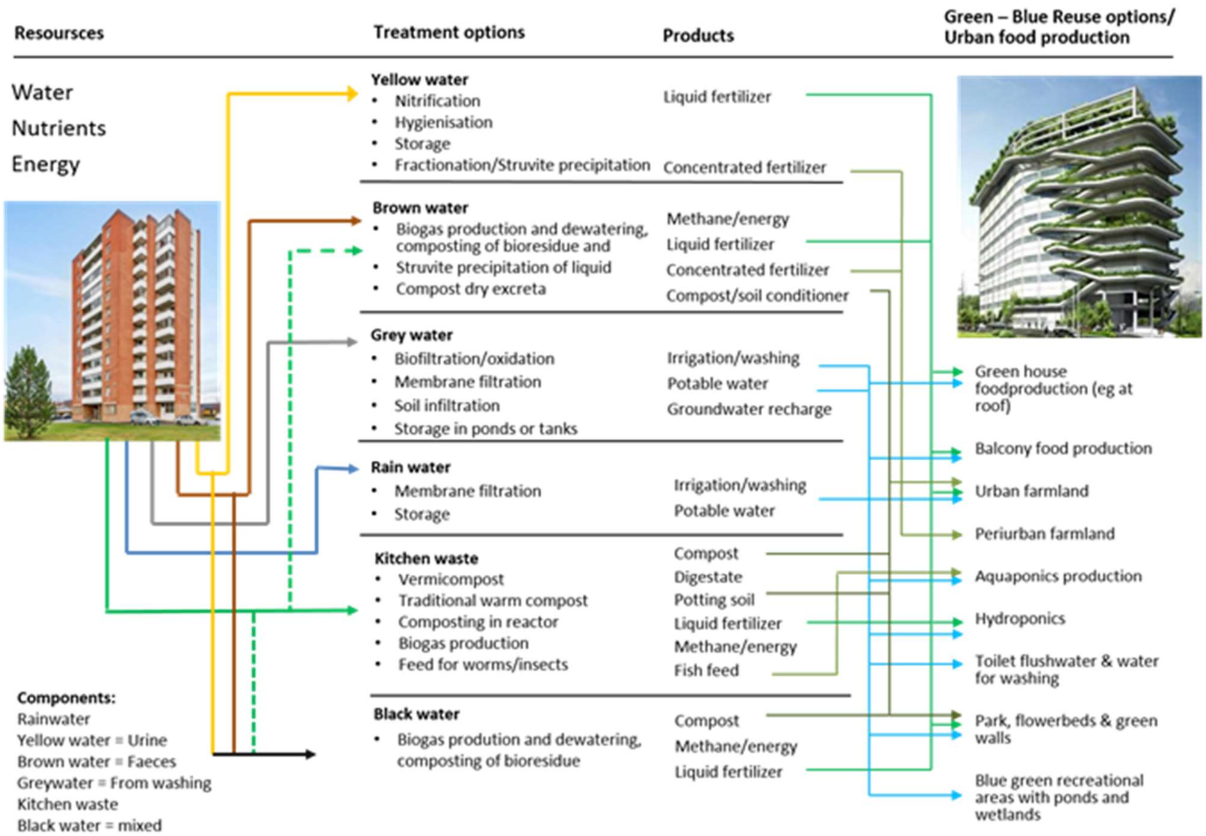

Figure 1: SiEUGreen model of recyclable resources

The blue technologies as presented in GA have been categorized as a) Technologies for processing of waste for recycling b) Technologies for source separation of wastewater (alternative toilet systems) c) Technologies for storm water handling. This deliverable D2.3 presents the updated status of the blue technologies under category a).

2.2 Technology readiness level (TRL)

The initial and target TRL level of the SiEUGreen technologies are given in the GA. The TRL level of the technologies range from 3-9. Once the technology is deployed in the showcase it will pass three distinct phases (i) testing of technology in open environment ii) measurable data collection to feedback research and iii) adjustment and improvement of the technology to raise the TRL level.

3. SiEUGreen blue technology fact sheets

This section provides the updated status of the technologies that are used for processing of the high strength wastewater, collected from vacuum and urine diverting toilets. The fertilizers produced as a by-product of this process can be utilized in the balcony gardens and the green house. The overview of the technology is given in the form of fact sheets. These technologies will be primarily implemented in the Fredrikstad showcase. The Schematic plan of the treatment system for organic household waste and blackwater in Fredrikstad is presented in Figure 2.

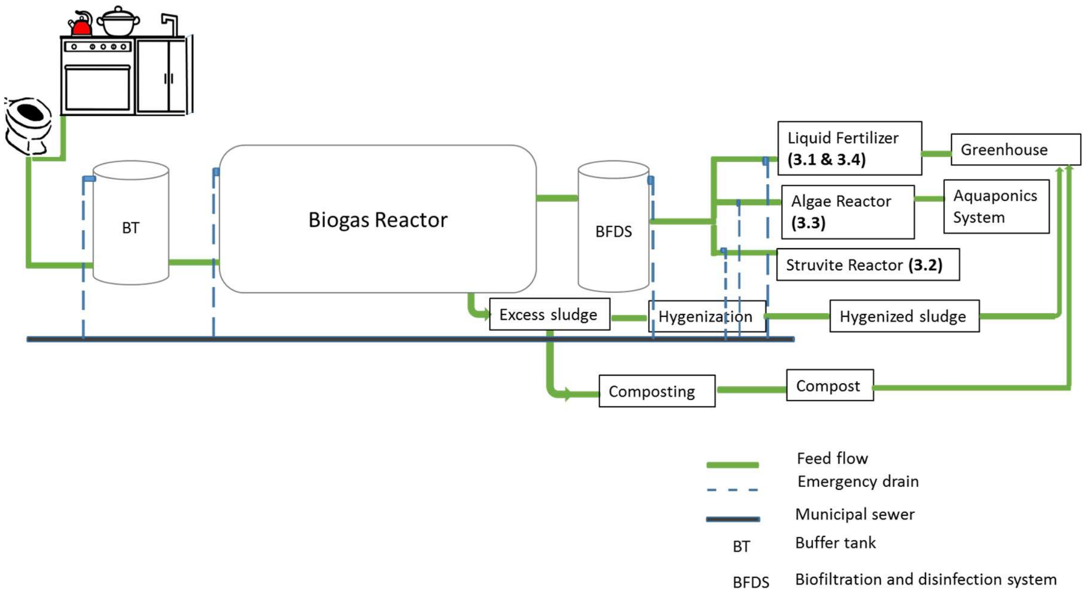

Fig. 2. Schematic plan of the treatment system for organic household waste and blackwater in Fredrikstad.

Additional information on the technology is presented in Annex 2.

3.1 Liquid Bio-digestate anaerobic digestion as a source of plant nutrients

Resources	Blackwater and organic household/food waste
Expected products	Liquid fertilizer (NPK), solid fertilizer (Struvite), and Microalgae biomass production
Green-blue reuse options	Fertiliser for urban and ex-urban farming

Short description of technology

Anaerobic digestion is a multi-step process governed by different groups of microorganisms and consisting of four main stages in series: hydrolysis, acidogenesis, acetogenesis and methanogenesis (Batstone et al., 2002, De Mes et al., 2003, McCarty and Rittmann, 2001). Through these complex and synergetic processes, the chemical energy contained in the wastewater is converted into biogas (electrical/heat energy). Moreover, due to the hydrolysis of proteins, carbohydrates, and lipids, organically bound nutrients converted into soluble inorganic forms and end up in the liquid phase. The most important nutrients are nitrogen (N) and phosphorus (P) mainly in the form of ammonium-N (NH_4-N) and phosphate (PO_4-P), respectively. These nutrients are important and are readily available sources for plant production. However, direct application of liquid digestate as fertilizer has been challenged because of health-related risks. Post-treatment of the anaerobically digested effluent is, therefore, an important step for safe and sustainable recycling and reuse of these renewable resources. Biofiltration with selective filter media and membrane technologies have shown promising results. Recent studies on anaerobically treated source-separated blackwater demonstrated a combined treatment and nutrient-recovery strategy and established mechanisms for a more dependable source of plant nutrients aiming at a circular economy (de Graaff, 2010; Zeeman et al. 2011; Eshetu, et al. 2018).

Process: The post-treatment of anaerobically treated liquid digestate involves a biofiltration system for removal of residual organic matter and suspended solids while the nutrients are conserved in the liquid phase (Eshetu, et al. 2018). The liquid digestate will then be further treated for removal of pathogens and micropollutants.

Process, environmental and operating parameters affecting the anaerobic process

The anaerobic treatment is a complicated process regulated by several factors. The factors such as wastewater characteristics, acclimatization of seed sludge, pH, volatile fatty acid (VFA), temperature, nutrients, presence of toxic compounds, loading rate, hydraulic retention time (HRT), liquid mixing and reactor design affect the processes of the growth of sludge bed, anaerobic digestion, biogas production and methane yield and effluent quality. This will determine the post-treatment level.

Types of nutrient recovery

- Direct use as liquid fertilizer after hygienization in BFDS (Fig. 2)
- Recovery of nutrients as concentrated liquid fertilizer (3.4)
- Recovery of nutrients in the form of struvite as slow release fertilizer (3.2)
- Recovery of nutrients in the form of microalgae biomass as biofertilizer (3.3)

Challenges: One of the possible risk for direct use as liquid fertilizer is NH_3 losses during storage and after land application. Ammonia loss can be minimized by producing a concentrated ammonium-nitrate liquid fertilizer through partial nitrification (see fact sheet).

Short description of planned SiEUGreen investigations

Biofiltration with selective filter media and membrane technologies have shown promising results and will be further investigated.

Preliminary evaluation of sustainability parameters

Ecology	High	Med	Low	N.A.	**Economy**	High	Med	Low	NA*
Treatment performance Phosphorus			X		Construction costs			X	
Nitrogen			X		O&M costs			X	X
Organic matter, SS	X				Cost-efficiency				X
Pathogens			X		Stability	X			
Resource recovery Nutrients	X				**Social**				
Energy	X				Social acceptance		X		
Biodiversity					**Technical**				
Landscape aesthetics					TRL levels	7-9			
Planned for use in showcase		Fredrikstad							

*NA = data not available or not relevant

3.2 Struvite precipitation from anaerobic digestion and urine

Source	Blackwater, digestate, urine
Expected products	Struvite - N and P recovery
Green-blue reuse options	Fertilizer for urban and ex-urban agriculture.

Short description of technology

To limit eutrophication potential of P removing P is becoming a requirement in many countries (Le Corre et al., 2009). On the other hand, the depletion of P resources and the growing demand of P fertilizer to support global food production has triggered the search for alternative renewable P sources (Cordell et al., 2009). Human excreta and animal manure are pointed to as two main renewable sources of P. P conservation in urban systems for urban agriculture is, therefore, an important step in the realization of food security through circular resource flow. Precipitation of phosphorus using Fe- of Al-salts is the dominating process for P-removal from wastewater. However, Fe- and especially Al- bound P has low plant availability due to low solubility at normal soil pH (Krogstad et al. 2005).

The precipitation of struvite ($MgNH_4PO_4 \cdot 6H_2O$) and its analogue, K-struvite ($MgKPO_4 \cdot 6H_2O$), from waste streams is widely recognized as a promising strategy for nutrient recovery owing to their elemental compositions and fertilizing properties (Shih and Yan, 2016). However, precipitation of Struvite requires concentrated waste streams as found in liquid from sludge dewatering, blackwater urine or animal waste. Hence, struvite cannot be easily precipitated from normal strength municipal wastewater.

Process:

Struvite is a white crystalline substance precipitated mainly as magnesium-ammonium-phosphate MAP ($MgNH_4PO_4 \cdot 6H_2O$) and K-struvite ($MgKPO_4 \cdot 6H_2O$). Struvite precipitation occurs in alkaline conditions when the concentration of Mg^{++}, NH_4^+ and PO_4^{-3} exceed the solubility products according to the following reaction (Bonmatí-Blasi et al., 2017).

$$Mg^{++} + NH_4^+ + H_2PO_4^{-3} \rightarrow MgNH_4PO_4 \cdot 6H_2O + 2H^+ \quad \text{(eq. 1)}$$

This process is influenced by a combination of physical and chemical parameters, mainly by pH, Mg:N:P molar ratio, reaction time, mixing speed, temperature and ion strength of competitive cations (mainly Ca and Na) that can form other salts with phosphate such as hydroxyapatite ($Ca_5(PO_4)_3OH$).

Precipitation of Struvite requires a pH adjustment usually close to 9 and ideally a stoichiometric ratio of Mg:N:P of 1:1:1. The ratio of Mg:N:P in wastewater varies significantly. Urine and blackwater have higher N compared to P and Mg content. Therefore, the pH has to be raised and Mg added. To remove high amounts of nitrogen, addition of both Mg and P required.

Struvite is relatively easy to precipitate in a batch process, but in the last decade several continuous processes are also developed (Ronteltap et al., 2010). The continuous processes are technically more sophisticated and, hence, suited for larger systems. For small volume flows, a batch process is considered the most cost effective solution. The most important control parameters for the struvite precipitation process is the pH, temperature, and source and dose of Mg.

Figure 1. Struvite precipitation from anaerobically treated source-separated blackwater at the NMBU laboratory.

SiEUGreen investigations

Precipitation of struvite from urine and anaerobically treated blackwater has been investigated in the NMBU laboratories. Seawater and MgCl2 has been used as magnesium sources as well as electroflocculation (see annex 2). The fertilizer quality and effect of struvite precipitated from anaerobically digested blackwater and organic household waste will be investigated.

Preliminary evaluation of sustainability parameters

Ecology	High	Med	Low	NA	**Economy**	High	Med	Low	NA*
Treatment performance Phosphorus	 X				Construction costs			X	
Nitrogen		X			O&M costs				X
Organic matter, SS	X				Cost-efficiency				X
Pathogens		X			Stability	X			
Resource recovery Nutrients Water Energy	 X X			 X	**Social**				
Energy			X		Social acceptance	X			
Biodiversity	X				**Technical**				
Landscape aesthetics	X				TRL levels				
Planned for use in showcase	Fredrikstad								

*NA = data not available or not relevant

3.3 Production of microalgae from biogas digestate as fodder for aquatic systems

Source of recourse	Treated biogas digestate
Expected products	Protein rich microalgae as fodder for fish and animals
Green-blue reuse options	Aquaponics, poultry farming

Short description of technology

Since the early fifties intense efforts have been made to explore new alternative protein sources as food supplements, primarily in anticipation of a predicted insufficient future protein supply (Becker, 2007). Microalgae are fast-growing photosynthetic organisms, which have the potential to be exploited as an alternative source of feed and food additives, biofuels, cosmetical ingredients, etc. (Hayes et al., 2017). The cultivation of microalgae, however, still is limited by the high cost of the biomass produced. Among the major costs encountered are the costs for nutrients such as CO2, nitrogen and phosphorous. Major advances in new production systems, designs and operations of continuously-run and closed loop photobioreactors, are promising to optimize microalgae biomass production. Moreover, recent studies have shown a sustainable feed production from algae using anaerobically digested effluent as a low-cost nutrient supplement (Kebede-Westhead et al., 2004, Chinnasamy et al., 2010). Liquid digestate contains abundant nitrogen [total nitrogen (TN): 139–3456 mg/l] (Wang et al., 2010, Kumar et al., 2010, Tuantet et al., 2014) and phosphorus [total phosphorus (TP): 7–381 mg/l] (Becker, 2007, Wang et al., 2010, Chinnasamy et al., 2010) as compared to the typical municipal wastewater. For the production of a high-quality fertilizer, and production of microalgae biomass for feed or food, it must be assured that unwanted micropollutants from the liquid digestate are removed (Escher et al., 2006). Moreover, to be used in aquaculture, a microalgae strain grown from wastewater has to meet various criteria, such as ease of culturing, lack of toxicity, high nutritional value with correct cell size and shape and a digestible cell wall to make the nutrients available (Patil et al., 2007) and low levels of heavy metals. Protein, polyunsaturated fatty acid and vitamin content are major factors determining the nutritional value of microalgae (Hemaiswarya et al., 2011).

Different types of microalgae production systems

Currently different microalgae mass production methods are available including open ponds and closed photobioreactors (PBR). These systems vary in performance, features, and technical and/or economic challenges. Many different designs for open-pond systems have been used in many places, but three major types operated at commercial scales are raceway ponds, circular ponds, and unstirred ponds (Shen et al., 2009). Closed PBR systems are systems that are not directly exposed to the atmosphere; instead, they are covered with a transparent material or contained within transparent tubing. The design of closed systems, consist of tubes of various shapes, sizes, and lengths constructed of various transparent materials such as glass and plastics. Photobioreactors are also widely designed as flat panel (plate) types to maximize light exposure. The high biomass productivity, reduced contamination risk, reduced CO2 losses and very important; better control of culture conditions, makes PBR more attractive than the open-pond systems. Although PBRs achieve 2 to 3 times higher biomass yield per unit surface area, volume-based construction costs of the PBRs could be higher. However, in a closed system where fast, efficient and continuous production system is installed, PBR microalgae production systems are potentially cost effective, especially when cheap nutrient sources are available.

Figure. Bench scale flat panel PBR for continuous C. sorokiniana cultivation using treated and diluted anaerobically treated blackwater (Photo: Melesse E.)

SiEUGreen investigations

In the Fredrikstad showcase, a microalgae production process is planned (annex 1). A flat panel or tubular photobioreactor microalgae production system will be tested at a pilot scale and the quality and effect of microalgae as fodder for aquaculture/aquaponics will be investigated.

Preliminary evaluation of sustainability parameters

Ecology	High	Med	Low	N.A	**Economy**	High	Med	Low	NA*
Treatment performance Phosphorus	X				Construction costs	X			
Nitrogen	X				O&M costs	X	X		
Organic matter, SS	X				Cost-efficiency				X
Pathogens				X	Stability			X	
Resource recovery Nutrients	X				**Social**				
Energy				X	Social acceptance				
Biodiversity				X	**Technical**				
Landscape aesthetics	X				TRL levels				
Planned for use in showcase	Fredrikstad								
Possible use in other showcases									

*NA = data not available or not relevant

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3.4 Nitrification of liquid waste

Source of recourse	Urine, liquid digestate, black water
Expected products	Stable and smell-free liquid fertilizer for application in greenhouses, balconies and for field crops
Green-blue reuse options	Urban and ex-urban agriculture

Short description of technology

Many liquid waste streams contain ample amounts of nutrients. To reduce smell and increase storability, oxidation of ammonium to nitrate can be an option. Nitrification also decreases pH which further stabilises the remaining ammonium.

In agricultural soil nitrification will usually happen quickly after application. When fertilizers made from liquid waste are used in large quantities in horticulture, it may be necessary to nitrify some of the ammonium prior to application. This is particularly true for plants grown with little or no soil (hydroponics), or for small or particularly sensitive plants.

SiEUGreen investigations

Two reactors are being tested at laboratory scale. One is based on a moving bed in a bioreactor where air is blown in. The other is based on a percolation biofilter. Urine is being tested as substrate, and some tests are also carried out using the liquid fraction of digestate (Annex 2). If reactors are implemented in a showcase, the performance will be investigated as also at pilot scale.

Preliminary evaluation of sustainability parameters

Ecology	High	Med	Low	N.A.	**Economy**	High	Med	Low	NA*
Treatment performance Phosphorus	X				Construction costs		X		
Nitrogen		X			O&M costs				X
Organic matter, SS		X			Cost-efficiency				X
Pathogens			X		Stability			X	
Resource recovery Nutrients	X				**Social**				
Energy			X		Social acceptance		X		
Biodiversity				X	**Technical**				
Landscape aesthetics				X	TRL levels	4-7			

Planned for use in showcase	Fredrikstad
Possible use in other showcases	Århus
Important references/other showcases in urban context	Nitrification of liquids – report on investigations is attached as Annex 1

*NA = data not available or not relevant

4. Research data to be collected to evaluate the technology in full scale operational environment

Technology	Research data to be collected in operational environment	Method of data collection
1. Treatment of Biogas digestate by biofiltration	• Performance of biofiltration system (hydraulic and organic loading), Energy consumption • Effluent quality (Nutrient content, pathogen, residual OM, TSS, turbidity and micropollutants)	Measuring, Registrations and/or calculation
2. Struvite precipitation from blackwater, anaerobic digestate or urine	• struvite production, N and P recovery, • Mg sources and Mg:N:P ratio • Effects of pH, reaction time, temperature on struvite formation • Quality of struvite (nutrient content, pathogen, residual OM, and micropollutants) • Plant response to struvite • Social acceptance	Registrations and/or calculation Interviews
4. Use of liquid digestate or urine for microalgae biomass production	• Microalgae biomass produced • Amount of N and P recovered • Protein, carbohydrate and lipid content of microalgae • Light energy consumption • Social acceptance	Registrations and/or calculation Interviews
5. Biofiltration of urine	• Amount of N recycled from waste production, • N emission • Quality of liquid fertilizer (smell, stability, nutrient value) • Social acceptance	Registrations and/or calculation Interviews
5. Nitrification of liquid waste	• Amount of N recycled from waste production, • N-emission • Energy consumption • Quality of liquid fertilizer (smell, stability, nutrient value, pathogens, micropollutants) • Plant response and productivity • Storage, transportation and application challenges • Social acceptance	Registrations and/or calculation Interviews

5. Adoption of the technology for implementation in the showcases

The selected technological options will facilitate the on-site treatment and safe recycling of resources from domestic wastewater and organic food wastes. Adoption and implementation of these technologies can play an important role in the urban environmental management system of the showcase areas. Improving agricultural productivity in the urban setting is key to transforming the livelihoods of people. The recycling of nutrients and organic substrates within the sources of generation enables local growing of herbs, vegetables, berries and flowers in the urban settings and thus, create a near zero-emission and full recycling of local resources.

It is important, however, to make sure that the chosen technologies are properly installed and monitored. Bad smell due to inadequate storage of waste, -ventilation or -treatment processes can be critical in urban areas, where people can be expected to live and stay close to waste treatment facilities. Hygienic issues are also important, both for the treatment and use of products in urban greening.

It will also be necessary to ensure that the operation and maintenance requirements of the chosen technologies are compatible with the levels of knowledge and skills available at the showcase. Lack of knowledge of these decentralized options and a shortage of qualified workforce and skills for operation and maintenance may limit the adoption of technologies to be implemented in the showcases. This requires a close researcher-user link.

Risk assessment will be done, and mitigation measures be ready at the stage of implementation. When data is collected, QMRA risk assessment will be carried out to estimate the health risk from the different treatment systems.

Risks and contingency plans

Risk	**Contingency plans**
Gas emissions (such as H_2S) from the biogas production system	Good ventilation, gas filtration system Gas detection alarm (methane) Signs showing NO SMOKING Fire extinguisher
Personal safety risks	Safety guidelines will be prepared and properly placed Treatment systems will be well protected from the reach of children.
Equipment operation failure risk	Overflows will be connected to emergency municipal drainage

6. Preliminary results of the laboratory test of the technology

Some of the laboratory based preliminary results are presented in the Annex 1 and 2 as a basis for implementation of the different technologies into the showcases.

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Annexes

Annex 1. The laboratory scale research experiments carried out in the research facilities of NMBU and NIBIO

1. Biofilm membrane reactor as a treatment step for reuse of blackwater

Project Acronym:	SiEUGreen
MSc. Thesis Research Title:	Evaluation of a biofilm membrane reactor as a treatment step for reuse of blackwater
Responsible MSc. Students	***Lukas Peder Fjeld Hansen***, Vann- og miljøteknikk, Fakultet for realfag og teknologi, NMBU.
Abstract:	Wastewater management has been and will continue to be practiced all over the world for many different reasons, including: the importance of reuse, the merging urbanization of cities, water shortages and the need for more compact wastewater solutions. A combination of some of these problems forms the basis of this study. In this study, a 9.2 L laboratory scale immersed biofilm membrane reactor (IMBR) with 5 ceramic membranes was utilized for investigation and evaluation for its treatment efficiency for the treatment and reuse of blackwater (BW). The laboratory scale biofilm MBR treatment unit was rigged late autumn of 2018 and operated from January until April 2019 for the purpose of the study. The MBR-reactor was investigated at 10-16 and 4 hour relaxation phases. The source separated BW used in this study was collected from vacuum toilets at the nearby Kaja student housings. After a start-up phase lasting for 3 weeks, the system reached a stable removal rate of 64.4 ± 13.7 % for soluble chemical oxygen demand (COD). The average concentration of total suspended solids (TSS) in the reactor fluid was 715.8 ± 177.6 mg/l and was reduced over the 0.2 µm ceramic membranes to a level under the detection limit. Transmembrane pressure (TMP) was monitored for both relaxation phases and the results showed significant rises in TMP-values for both running operations. For 10-16 hour relaxation phases, the longest batch run lasted for 1984 minutes and 5596 minutes for 4 hour relaxation phases before transgression of a set TMP-alarm value of 20-25 mbar. Average run time for 10-16 hour relaxation

	phases was 533 ± 321 min and 285 ± 943 min for the 4 hr relaxation phases during the 3-week start-up phase. Volatile fatty acids (VFA) was sampled from reactor fluid and permeate to elucidate the process in the filter cake and biofilm layers on the membrane surface more in detail. Foaming in the reactor was monitored daily for further characterization and explanation of possible membrane fouling contribution. An investigation of total coliform bacteria and *E. coli* was done at the end of the period with 4 hour rest phases and resulted in a concentration below the detection limit when exposed for UV light for the membrane permeate. The membrane bioreactor performed well under highly robust conditions. Overall the result from this study gives an understanding of the possibilities and limitations regarding treatment of BW using IMBR.

2. Nitrification of liquids – report on investigations

Introduction

In nature ammonium is released from decomposition of organic material or from hydrolysis of urea and other nitrogen containing compounds. Mineral nitrogen (N) occurs in two chemical compounds, nitrate and ammonium. Nitrification is microbial oxidation of ammonium to nitrate. This happens naturally in soils (Beeckman et al. 2018) and during composting (Cáceres et al. 2018). In soil that are cold, anoxic or have low pH there may be little nitrification, and the main source of mineral nitrogen will be ammonium. Many crop plants however, grow poorly with ammonium as the only N source (Phipps and Cornforth 1970). Furthermore, because nitrate is more mobile in soil than ammonium, it makes uptake of large quantities possible even with a small root system.

Many liquid waste streams contain ample mineral nitrogen as ammonium. Examples are digestate, greywater, stored urine. Ammonium is easily lost from liquid solutions as ammonia gas if pH is alkaline. Ammonia volatilization also makes the solution smell. Nitrate is stable, although small amounts can be lost by denitrification and it is vulnerable to leaching losses from soil. Both ammonium and nitrate can be taken up by plants, but many plants do not grow well with ammonium as the only source of N. During nitrification, pH is also decreasing, which also contributes to stabilizing remaining ammonium.

Nitrification can also take place in a liquid, but the process requires ample oxygen, so air must be blown in. This is the first step in sewage treatment (Massara et al. 2017). Aquaponics systems have a nitrification step to make the water from the fishpond suitable for the crops. Successful nitrification of diluted urine has also been reported (Feng et al. 2008). It is more challenging in liquids with higher nitrogen concentrations, but there are reports of successful nitrification in digestate (Botheju et al. 2010) and almost full-strength urine (Fumasoli et al. 2016; Udert et al. 2003; Udert and Wächter 2012).

An alternative to a reactor is some sort of biological filter with porous media, where the liquid percolates over. The advantage of this is that it is easier to ensure adequate oxygen supply since the liquid is constantly in contact with air. There are also many systems based on this principle for wastewater treatment, e.g. sand filters and other packed-bed filters with single-pass or multipass (recirculation), but the performance for nitrification is largely unknown for nitrogen rich liquids as urine and digestate.

Nitrification is a two-step process with each step performed by different microbes, although there are now reports of some microbes from oligotrophic environments able to perform both steps (Beeckman et al. 2018). The two-step process (Anthonisen et al. 1976) is shown in the following equation:

$$NH_3 \xrightarrow{\text{AOB}} NO_2^- \xrightarrow{\text{NOB}} NO_3^-$$

Ammonium oxidizing bacteria (AOB) and nitrite oxidising bacteria (NOB) does the first and second step respectively. Both processes also liberate H^+, so that pH is reduced. NOB grows slowly, on surfaces, whilst AOB can also grow freely in solution and they can also grow faster than NOB under good conditions. Accumulation of the intermediate product, nitrite is therefore often a problem (Sun et al. 2012). Conditions should be made so that growth rates of NOB and AOB are similar, and the hydraulic retention time should be so short that no significant populations of AOB can establish in the solution (Fumasoli et al. 2016). A temperature of around 16˚C and pH below 6.6 has been shown to promote a balanced ratio between AOB and NOB (Hellinga et al. 1999). Any system or reactor for nitrification should aim to promote stable conditions that give a balanced ratio of AOB and NOB.

Nitrification of liquids in urban agriculture can be to reduce smell, make the liquid more stable in storage and make it a better plant nutrient solution. If the purpose is only to improve it as plant nutrient, nitrification can be performed on diluted solutions, just before used for watering plants in greenhouse etc. If the purpose is to increase storability, nitrification should be performed on higher strength solutions, which is harder to achieve.

The aim of this work was to get nitrification of nutrient liquids potentially available in urban agriculture to work at as high concentration as possible, to find out what problems and issues need to be considered, and to compare different methods.

Materials and methods

Two main types were tried, bioreactor and biofilter.

Bioreactor

The bioreactor had an inner volume of 2.5 L and is shown schematically in Figure 1. Cooling liquid circulated around it as indicated in the figure, ensuring that the temperature was kept constant close to 15 degrees. At the top there was a lid of silicon with a number of holes for in- and out-flow of the liquid and air and for sensors, as indicated in Figure 1. In the bottom there was a magnetic stirrer and a perforated sheet of plastic above it. Air was blown in from below.

The system was regulated and monitored by a program, lab VIEW. Temperature and pH was regulated. If pH increased above a setpoint more substrate was automatically added. At startup pH in urine was increasing due to hydrolysis, and then acid was added instead when pH dropped below a setpoint. The setpoint was normally 6.2, but some variation was tried.

At the start in early 2018, the bioreactor was set up as packed bed bioreactor with a layer of Leca with biofilm collected from VEAS sewage treatment plant. This was set up again a couple of times after nitrite accumulation was encountered. Eventually Leca was exchanged with moving beds (KMT carrier K1) in late 2018 (about 50% full). A small amount of Leca from VEAS was added as well to give inoculum.

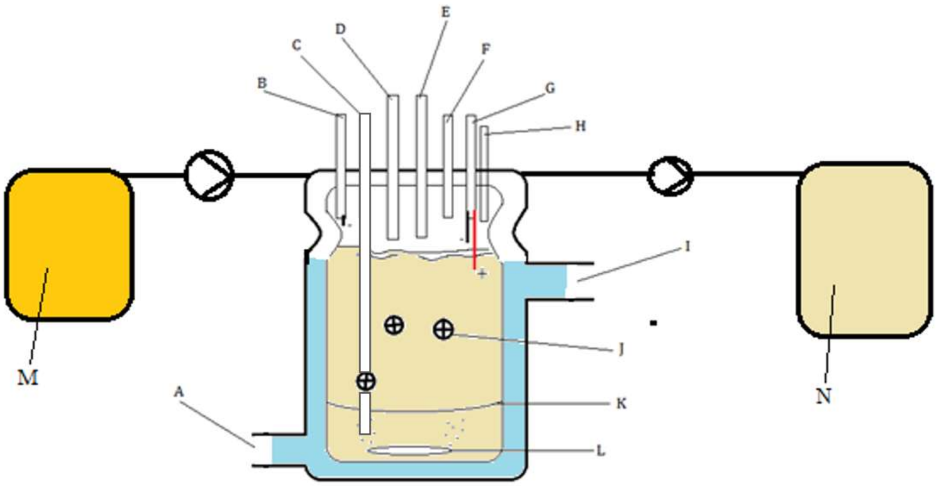

Figure 1: Biorector: M = substrate tank, N = product storage tank, A,I = In- and outflow of cooling liquid, L = magnetic stirrer, K = perforated plastic layer, J = biofilm carriers, B = substrate inflow, C, F = air in- and outflow, D, E, G, H = sensors for dissolved oxygen, pH, liquid level. Substrate was automatically added when pH dropped below a setpoint and product was sent to storage tank when the reactor was filled above a threshold. Substrate and product weight were registered automatically, and data stored in a PC program together with sensor values.

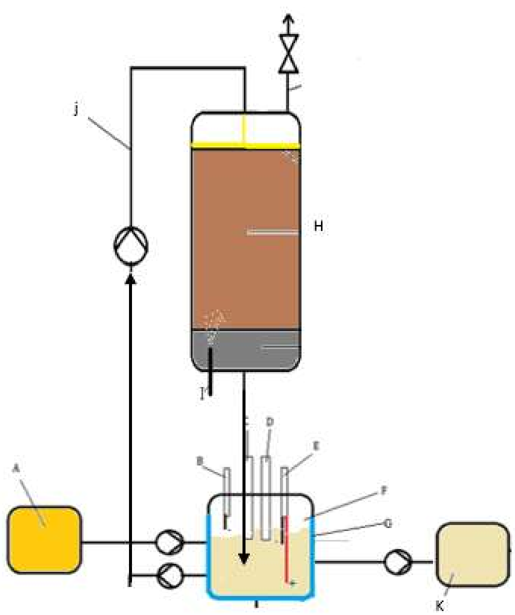

Figure 2: Biofilter laboratory trial: A = substrate, C-E = sensors, O_2, pH, F = intermediate tank for sensor and mixing, G-cooling liquid for temperature control, H=Biofilter with porous media, I = air inflow and outflow on top of reactor, J= tube with pump to make the solution circulate, K= product storage tank (pumps were controlled by pH set point in A and K). Control system was similar to bioreactor.

Biofilter

The setup is shown in Figure 2. The filter material (Leca, grain size 4-10 mm) was filled in a column with height 44 cm and diameter 6 cm. Particle density was 540 g/L. 10% of the Leca used was from VEAS with biofilm as inoculum. The control system was similar to the bioreactor, and sensors and in- and outflows were mounted in a container outside the biofilter (Figure 2).

Substrate

Both reactors were run with diluted stored urine. Concentration was increased slowly. In early 2019, this was done as part of a master thesis (Enoksen 2019). After that the bioreactor was run with diluted digestate from the biogas plant testing for SIEUGREEN. The highest concentration used 50% for urine and 30% for digestate.

Sampling and analysis

In the beginning, amount of nitrate and nitrite were only assessed using strips, for process control. Later some samples were also collected of products and substrate. The samples were frozen (-20°C) until analysis on ion chromatograph (858 Professional Sample Processor).

Storage stability and smell

Some product was stored on the laboratory bench to be compared with the frozen sample, to see if it was stable during storage. The longest storage time was just under a month. Nitrite, nitrate and ammonium in stored and frozen samples were compared using paired t-test (minitab v18). Smell was assessed by smelling the product. The product was used as fertilizer for potted plants.

Results and discussions

In the packed bed bioreactor, nitrite always started to accumulate after a while. Nitrite levels up to 200 mg/L were recorded (data not shown). The reason is probably that oxygen finds only some routes through the Leca layer, and patches with insufficient oxygen may develop even when overall measurements show sufficient oxygen. It is also possible that too tick biofilm of heterotrophic bacteria developed. In the sewage treatment plant, Leca is backwashed every day to avoid this (Wien et al. 1995). Diluted urine contains much less organic matter per unit mineral nitrogen than sewage water, but still it may need to be washed occasionally to perform over time.

The moving beds performed much better, and only small amounts of nitrite were found (Figure 3). The product contained an appropriate mix of nitrate and ammonium, nitrate to ammonium ratio 1±0.7.

Digestate contained more suspended organic matter than urine, causing occasional blocking of the tubes. The readings of dissolved oxygen were also much lower (although variable), but this still did not lead to nitrite accumulation.

Initially the biofilter accumulated nitrite. After the initial period and with pH stabilization of substrate the biofilter worked well for substrate up to 25% (Figure 4). An ammonium to nitrate ratio of 1,2 was achieved with an estimated loss of 13% nitrogen. New results suggest that even higher concentration may be possible (data not shown). As this system was run shorter than the bioreactor, we still do not know its full potential.

There was no significant change during storage. The product had little or no smell. No controlled experiments on use as a fertilizer were performed so far, but chemical analyses of the produced liquid show a balanced nutrient content suitable for plant nutrition. All indications are that it performed well, no adverse effects were encountered.

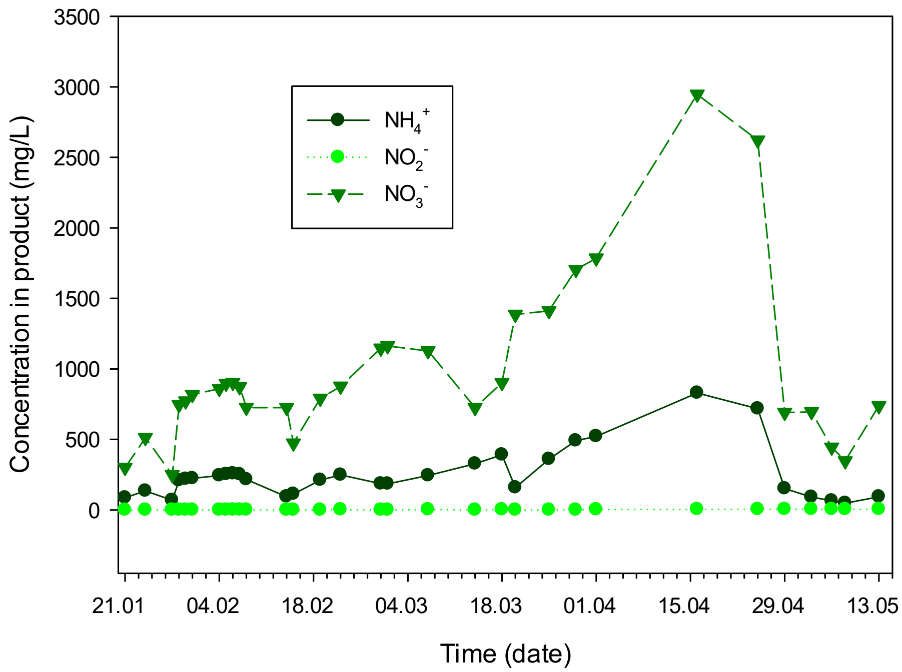

Figure 3: Ammonium, nitrite and nitrate in product in moving bed bioreactor. Input was to start with diluted urine: 21.-28.1: 5%, 29.1-8.2: 10%, 9.-19.2: 20%, 21.2-7.3: 10%, 8.3-1.4: 15%, 2.4-24.4: 25%. Then input was changed to digestate: 25.4-13.5: 25%.

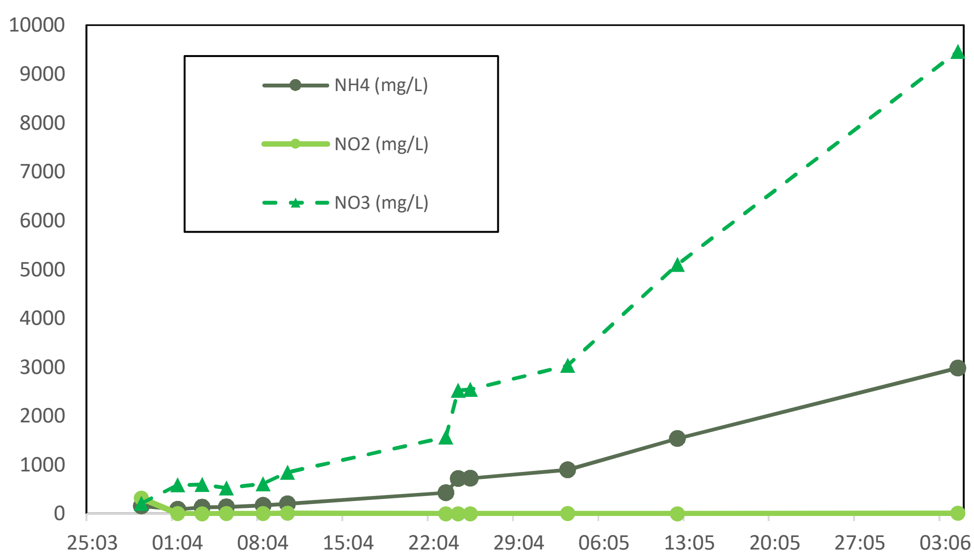

Figure 4. Ammonium, nitrite and nitrate in the biofilter product. Input was diluted urine: increasing gradually from 5% to 50% substrate in the period 28.03 to 05.06.

Conclusion and outlook

The results show that stable nitrification of ammonia rich liquids in a bioreactor is possible. Further work will focus on adapting it to even higher concentrations (ideally full-strength urine), and to develop systems able to cope with higher amounts of suspended organic matter. Furthermore, the biofilter system will be further developed and tested. It is possible that this system could be better able to deal with high strength urine, because ample oxygen is believed to available when the liquid is in contact with air in the filter.

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Annex 2 Details of the technology ready for implementation in the Fredrikstad showcase

The Fredrikstad showcase will utilize waste resources from an apartment building having 64 apartments (Fig. 1) to produce bioenergy and growth media for local (urban) agriculture.

Fig. 1. Part of the environmental housing development at Cicignon park in Fredrikstad. The highrise building to the right contains 64 apartments connected to the circular economy system to be demonstrated. The treatment facilities for the toilet waste (blackwater) and organic household waste is located underground under the area for wetland treatment of greywater. The waste-based products will used in on-site urban agriculture including the greenhouse to the lower left in the picture (drawing by Niels Torp architects).

Green and blue technology

The urban farming will include balcony gardens, garden plots on ground level and a greenhouse with soil based, hydroponic and possibly also aquaponic cultures, but this is not yet confirmed.

The soil like growth media is based on compost of the solid fraction of digestate and from other solid waste fractions as garden waste and organic household waste. The fertilizer will be derived from wastewater and organic household. The system is based on collection of blackwater and organic household waste through a vacuum system from a minimum of 14 apartments (Fig 2).

Prior to the anaerobic (biogas) reactor there is a buffer-tank where it is possible to manipulate the influent if needed; e.g in Christmas time when Norwegians consume large amounts of

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citrus fruits that may affect the stability of the anaerobic reactor (Fig 3). The buffer tank and the subsequent tanks and treatment units can all be drained to the municipal sewer if something goes wrong or for maintenance purposes (see dotted lines Fig. 3). These emergency drains increase the robustness of the system in the early priming face especially.

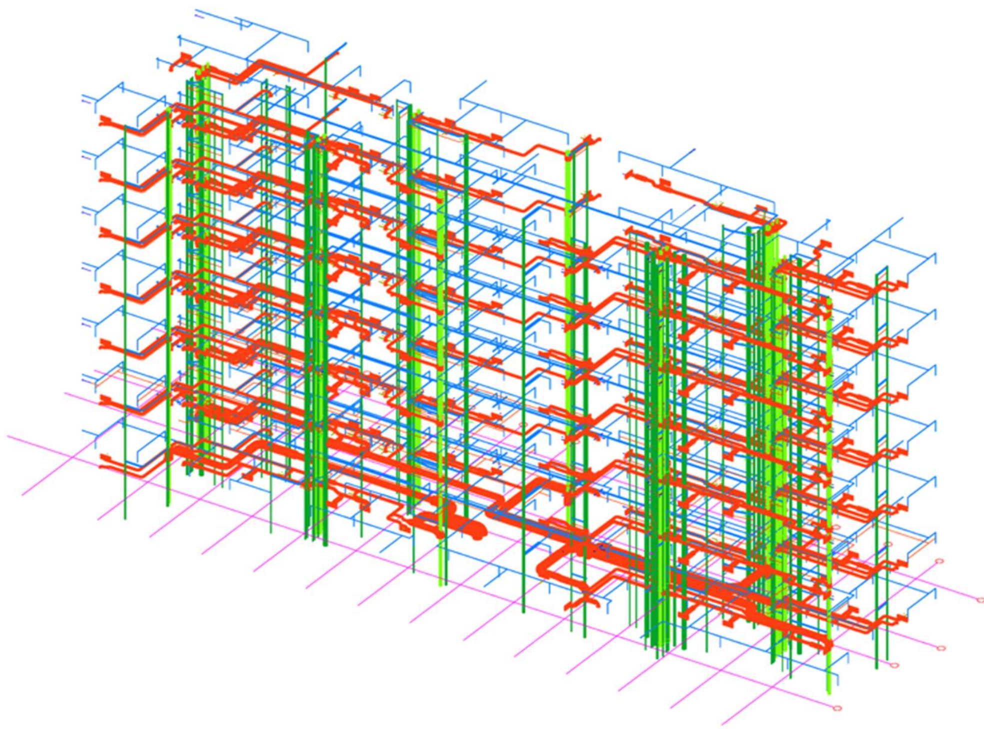

Fig. 2. Plan for pipes in the Fredrikstad showcase.

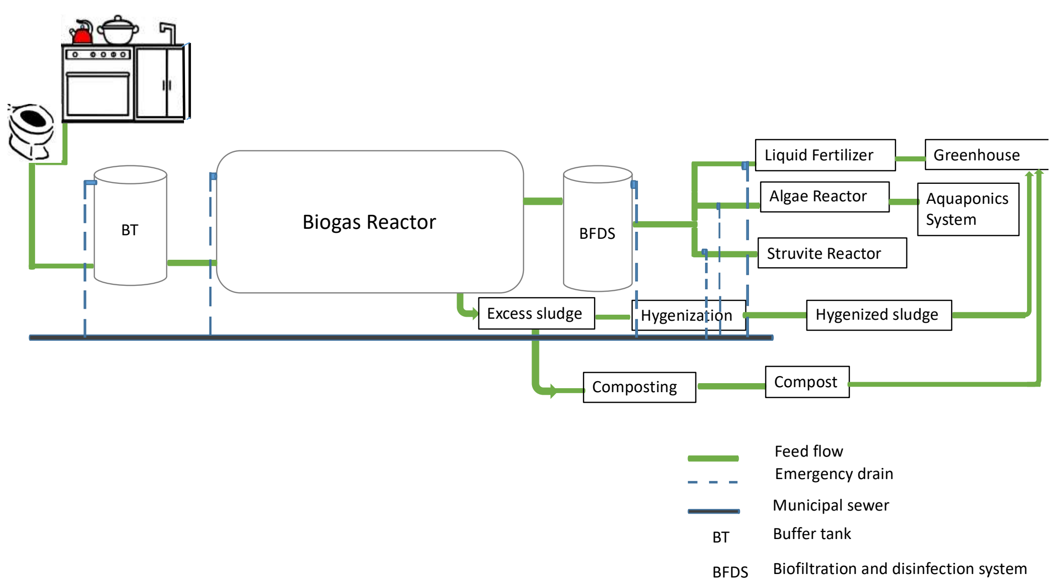

Fig. 3. Schematic plan of the treatment system for organic household waste and blackwater in Fredrikstad.

The effluent from the anaerobic reactor will be filtered before it is split into 3 lines producing liquid and solid (struvite) fertilizer and algae (Fig.3). The liquid fertilizer will be used in hydroponic cultures in the greenhouse. The struvite will be used in balcony gardens and the garden plots planned outside the apartment building. Preliminary results of experiments on urine and anaerobically treated blackwater for struvite precipitation using seawater and Mg-plates (with and without current) demonstrated promising options as alternative sources for Mg. The P recovery results with seawater and Mg plates were higher compared to MgCl2. About 91 % P (with 1.3:1 seawater:urine volume ratio) and 94 % of P (with 4:1 seawater:urine volume ratio) were recovered as struvite from urine using seawater compared to 85 % P recovery using MGCl2 (Richter, 2018). Concentrations of total C and total N in the precipitates were 1.8 % and 1%, respectively. On the other hand, the experiment on anaerobically treated blackwater using Mg-plate with electric current as source of Mg removed 93 % and 98 % of P at pH 7.4 and pH 9, respectively. Moreover, the analysis on the concentrations of Ca2+, Mg2+ and P in the precipitates indicated that seawater treated struvite had higher Ca than on MgCl2 treated struvite precipitates. This is mainly due to the high Ca concentration in seawater. The Mg and P concentrations in the precipitates were comparable. Similar results on Mg and P concentrations observed on Mg-plate treated precipitate of the anaerobically treated blackwater. The total N concentration in the Mg-plate treated struvite precipitate ranged from 4.1 to 7.6 % while the total C concentration remained low (from 0.8 to 1.2 %). However, in all the scenarios outlined above, it is important to emphasize the need for further research involving analysis of the actual Mg:P ratios of the different sources used instead of their volume ratios. In addition, more data sets are required to reach with sound conclusions, in terms of both ease of operation and management, economics, and struvite quality (presence of impurities).

The algae will be used for the aquaponic system or as green fertilizer. The treatment system is planned installed underground (Fig. 4). On top of the treatment facility the wetland part of the greywater treatment system is located. The wetland will be penetrated by a shaft so as to give room for an overhead window providing light to the treatment room and visitor center (Fig. 4.) The underground room will contain the components from Fig. 3. The treatment components will be displayed behind transparent walls. The intention is to design the treatment room as a learning or visitor center open to the general public, school classes, students, scientists and others interested. However, the pedagogical features of the learning center is pending additional funding.

The goal for the greywater (water from washing, shower and kitchen) treatment is to reach bathing quality with respect to indicator bacteria greywater and an average effluent concentrations of 1ppm for total phosphorus and less than 10 ppm for total nitrogen. The greywater can then be discharged to the stormwater system. The planned treatment system consists of a septic tank, biofilter and a subsurface flow wetland (Fig. 6).

Preliminary results from the experiment to convert greywater into drinking water were promising. However, examination of pharmaceutical and personal care product (PPCP) residues was not included in this study. Further investigation on the removal efficiencies of the treatment systems on PPCPs and the risk that may cause is necessary to satisfy the use of treated greywater as alternative drinking water sources.

Fig. 4. The planned room for treatment of blackwater and organic household waste and fertilizer production. Treatment happens behind transparent walls and a window in the roof provides light. The room is planned as a visitor center displaying circular economy (drawing by Niels Torp architects)

Green walls for greywater treatment have been promoted based on research in NMBU (Svete 2012, Eregno 2017), but the developer, who is concerned about his economy, has not yet approved this idea. However, the walls will be green due to large sections and supports for growing plants on the balcony gardens (Fig. 5).

The stormwater will mainly be handled on site in a large central pond system (Fig 1). The soil is mainly clay. Infiltrometer measurements by Amundsen and Sleipnes (2019) showed that only the upper 30 cm had any infiltration and storage capacity so the stormwater mitigation could not be based on substantial infiltration.

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Fig. 5. The south fasade of the 64 apartment building

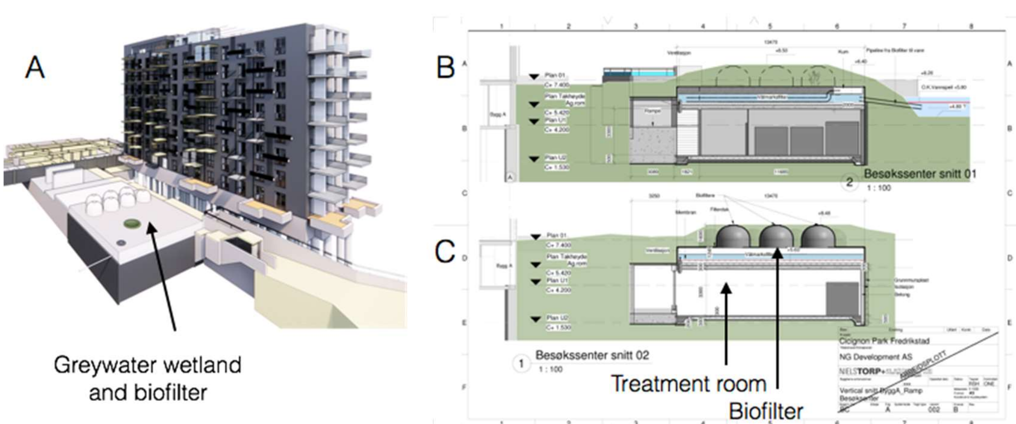

Fig. 6. The greywater wetland and biofilter. A: 3D drawing, B: Cross section west-east, C: Cross section south-north.

Yellow technologies

The yellow technologies in Fredrikstad consist of using solar photovoltaic (PV) panels, solar collectors and heat exchange with the underground - borehole thermal energy storage (BTES) if the hydrogeological conditions are favorable.

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NMBU produced model in excel by which the solar energy collected on the apartment building could be estimated. The model showed that the electricity demand was far from being covered even if the all possible wall and roof areas were covered by PV-panels. The developer contacted a consultant that did not recommend PV-panels for economic reasons. The only PV panels and solar collectors that are currently planned is therefore on the roof of the building where the developer plans to have a restaurant (Fig 1). There are also discussions with the developer regarding the placement of a solar driven dry toilet in connection to the roof restaurant.

Fredrikstad municipality has demanded that the building hooks up to the municipal district heating system. The Fredrikstad district heating system is based on burning of municipal solid waste. In the summer time the system has surplus energy that can be purchased at a low price. If this heat can be stored underground and reused in the cold season the heating cost of the building may be reduced.

Investigations to determine the feasibility of BTES are under way. Three wells have been drilled to investigate hydrogeological properties of the underground (Fig . 7.).

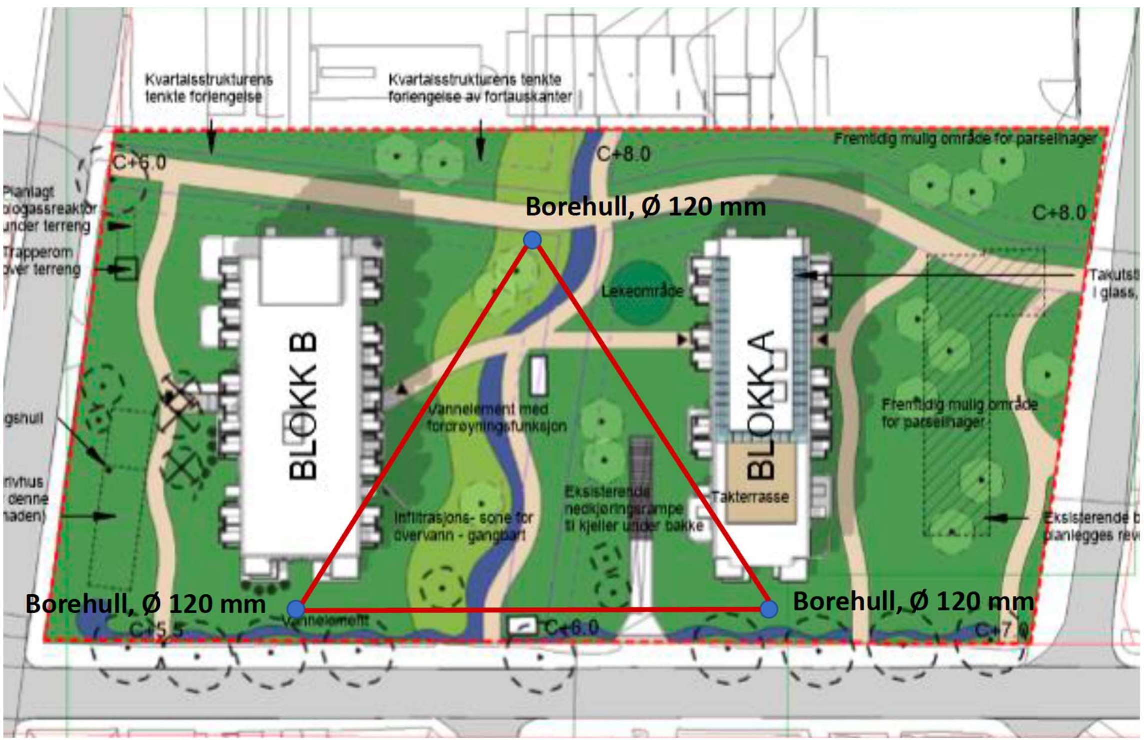

Fig. 7. Location of the wells drilled for investigating borehole thermal energy storage (BTES).

The soil cover is clay and the distance to the granite rock varies from 4 to 11 meters. The drilling indicate that the granite is only moderately fractured. Work is under way to model the groundwater flow and potential heat loss. The selection of heating system is pending these investigations.

The waste and wastewater handling system (Fig. 3) has been assessed with respect to energy aspects and compared to the existing system in Fredrikstad called FREVAR (Fig. 8). This preliminary assessment shows that the SiEUGreen concept should be able to operate with a net positive energy balance of 123 kWh/pe/year whereas the large municipal system FREVAR today operates with a net energy need of 107 kWh/pe/year. It must be stressed that this is a preliminary analysis and that a more comprehensive analysis will come when monitoring data of the SiEUGreen system are available. However, the preliminary assessments indicate that the SiEUGreen system is more sustainable than the FREVAR system with respect to the elements included in this analysis.

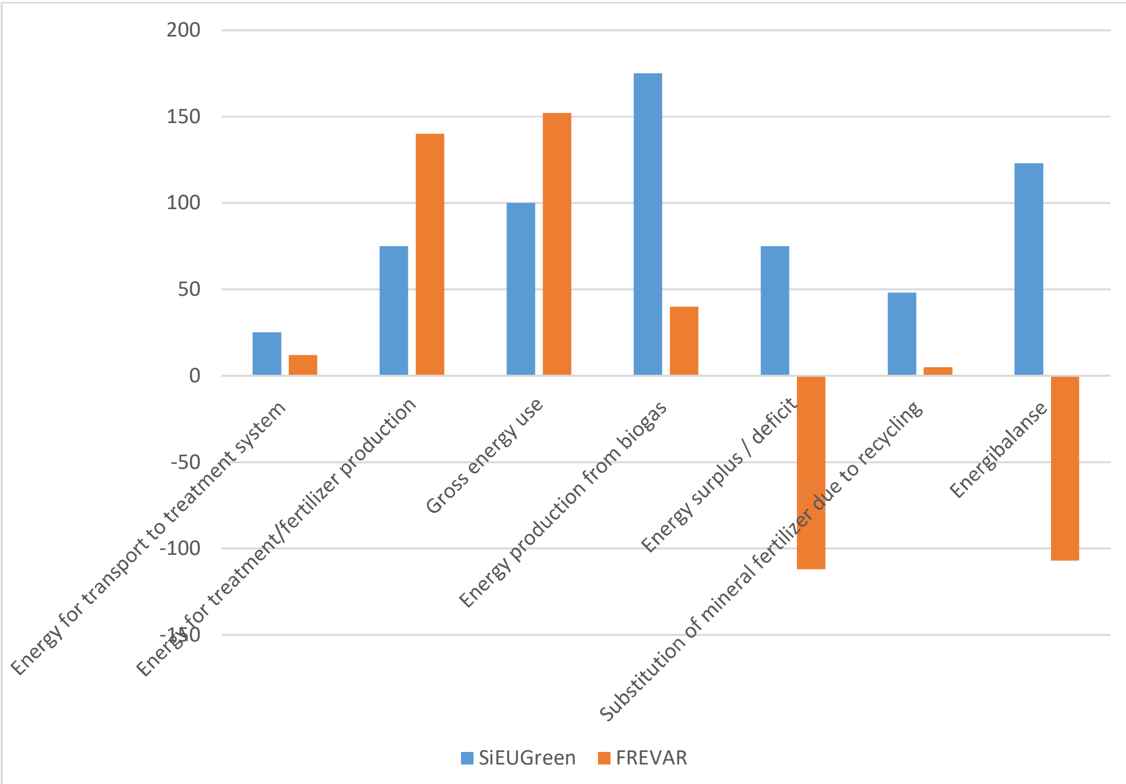

Fig. 8 Energy aspects of waste and wastewater treatment.

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SiEUGreen
Sino-European innovative green and smart cities